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# Impacts of land use and climate change on carbon dynamics in south-central Senegal

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## Abstract

Total carbon stock in vegetation and soils was reduced 37% in south-central Senegal from 1900 to 2000. The decreasing trend will continue during the 21st century unless forest clearing is stopped, selective logging dramatically reduced, and climate change, if any, relatively small. Developing a sustainable fuelwood and charcoal production system could be the most feasible and significant carbon sequestration project in the region. If future climate changes dramatically as some models have predicted, cropland productivity will drop more than 65% around 2100, posing a serious threat to food security and the efficiency of carbon sequestration projects.


*Keywords:* Carbon cycle; Carbon sequestration; Sustainable development; Data-model fusion; Biogeochemistry; Fuelwood production

## 1. Introduction

The continuing rise of atmospheric $CO_2$ concentration will most likely affect the stability of Earth's climate system, the health of humans, and the sustainability of socioeconomic systems (IPCC, 2001). Carbon (C) dynamics in terrestrial ecosystems has been one of the major factors affecting $CO_2$ concentration in the atmosphere

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(Houghton, 1999; IPCC, 2001; Pacala et al., 2001; Schimel et al., 2001). Quantification of the spatial and temporal variability of C sources and sinks at regional to global scales has been challenging because land–atmosphere C exchange is influenced by many factors, including land use and land cover change (DeFries et al., 1999; Houghton et al., 1999), $CO_2$ fertilization (Schimel et al., 2000; Tian et al., 2000; Cao et al., 2001), nitrogen fertilization (Nadelhoffer et al., 1999), and climate variability and change (Schindler and Bayley, 1993; Keyser et al., 2000; Cao et al., 2001; Bachelet et al., 2001). Nevertheless, to slow the rising rate of atmospheric $CO_2$ concentration, developing countries can sell C sequestration credits to developed countries for offsetting C emissions through the Clean Development Mechanism (CDM) under the United Nations Framework Convention on Climate Change (UNFCCC) (IPCC, 2000). Carbon sequestration resulting from afforestation and reforestation activities since 1990, carried out as C sequestration projects, is eligible for such credits during the first commitment period (i.e., 2008–2012), and C sequestration in other C pools, such as soil organic carbon (SOC), could become tradable for the subsequent commitment periods.

To set up a successful carbon sequestration project in a region, one must first estimate its carbon sequestration potential during the life time of the project, considering biological, physical, social, economic, and political constraints. That is how much additional carbon will be sequestered owing to the implementation of a CDM (IPCC, 2000; Pfaff et al., 2000). The additional C sequestrated is an ideal measure of "certified emissions reductions" (CERs), which can be traded publicly. If CERs are inaccurate, trading could lead to increased global net emissions and efforts to sequester C in terrestrial ecosystems will be misdirected and inefficient. In addition, over rewarding C sequestration would anger environmentalists (because the carbon sequestration practice would not help alleviate the increase in atmospheric $CO_2$ concentration) and the supplier's competitors, while underpaying for honest effort may discourage suppliers.

Therefore, methods are needed to quantify the spatial and temporal dynamics of C sources and sinks at the local, regional, and global scales to help understand the major processes and driving forces that define the contemporary and future $CO_2$ exchange between the land and the atmosphere and to successfully implement the CDM. Although many biogeochemical models have been developed at various spatial and temporal scales, few models have the capability of simulating C dynamics over large areas with a spatially explicit, dynamic consideration of land use and land cover change (Melillo et al., 1995; Tian et al., 1998; Cao et al., 2001). This paper first describes and illustrates how a model may be built to simulate carbon dynamics in space and time, with a special emphasis on the fusion of land use change data into model simulations. Then, the model is applied to estimate the spatial and temporal changes of C stocks in south-central Senegal from 1900 to 2100. Finally, management options are discussed from the perspective of carbon sequestration potential and regional sustainable development.

## 2. Methods

### 2.1. Study area

The Department of Velingara is located in the south-central part of Senegal, covering an area of 543,414 ha. The mean annual precipitation from 1961 to 1996 was 843 mm with a distinct rainy (June–October) and dry season (Fig. 1). The mean monthly temperature is 28.1°C, fluctuating monthly between 24.4°C and 32.1°C. Details of the characteristics of the region are given (Wood et al., 2003). Land use and land cover change information was derived from Landsat images acquired in 1973, 1978, 1984, 1990, and 1999. For a detailed description of the methodology for analyzing land use/land cover change, see Section 4.1 (Wood et al., 2004).

### 2.2. Field studies and model parameterization

Vegetation attributes, including canopy cover, tree height, diameter at breast height (DBH), and grass biomass, were measured in circular experimental units 40 m in diameter around six villages in representative sites of the major land units in the region (i.e., cropland, parkland or cropland with trees, fallow, savanna, and dry forest). Carbon stocks in above-ground vegetation were calculated by using the allometric formula recommended by the Food and Agriculture Organization (FAO) for the calculation of the tree biomass of tropical dry forest (Brown, 1997). Root biomass of trees and herbs was estimated as 0.35% and 0.15% of the above-ground biomass, respectively, based on field observation. A factor of 0.47 was used to convert the total biomass to total biomass carbon (Nadelhoffer and Raich, 1992).

Carbon accumulation rate in fallows was estimated using a chronosequence approach (Manlay et al., 2002a, b). Different ages of fallows were chosen at each site and their C stocks were measured. This approach assumes similar soil, climate,

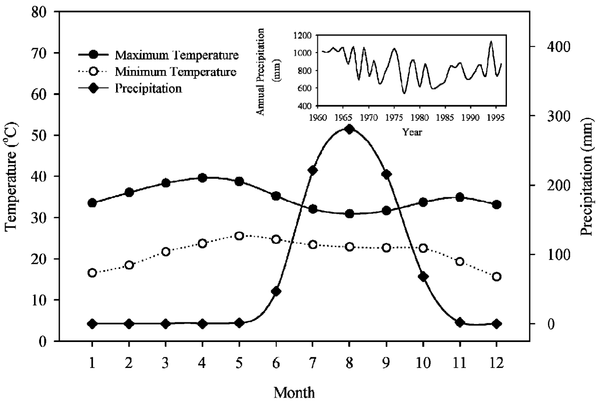


Fig. 1. Mean monthly precipitation, maximum and minimum air temperatures, and annual precipitation fluctuations from 1961 to 1996 in Velingara.

disturbances, and management practices for all the plots at each site. Fallow age was determined using two complementary methods: interviewing the plot owner and counting the number of age rings on sections of stems of *Combretum glutinosum* Perr.ex DC. and *Detarium microcarpum* Guill.et Perr., presenting definitely discernible rings. The estimate of above-ground biomass was carried out with allometric equations established for four principal species of the fallow (*Terminalia macroptera* Guill.et Perr., *Piliostigma thonningii* (Schumach.) Milne-Redh., *C. glutinosum*, *Combretum geitonophyllum* Diels), representing between 70% and 80% of trees. These equations were then applied to an inventory of diameters of all the stems in the plot samples. Root biomass was estimated according to an excavation study conducted at similar sites (Manlay et al., 2002a).

Soil sampling was conducted in 2002 at the sites where vegetation characteristics had been measured. Soil samples were collected at 0–40 cm depth with two repetitions for the determination of SOC content and bulk density. To compare model-simulated SOC stocks (0–20 cm) with field measurements, we calculated SOC stocks in the top 0–20 cm layer from those in the 0–40 cm layer using a global average conversion factor of 0.64 (Jobbagy and Jackson, 2000).

### 2.3. Modeling approach

#### 2.3.1. Structure of general ensemble biogeochemical modeling system

Carbon dynamics in vegetation and soils was simulated using the general ensemble biogeochemical modeling system (GEMS) (Liu et al., 2004) at the spatial scale of 80 m. GEMS is a modeling system that was developed for a better integration of well-established ecosystem biogeochemical models with various spatial databases for the simulations of biogeochemical cycles over large areas. It uses a Monte-Carlo-based ensemble approach to incorporate the variability (as measured by variances and covariance) of state and the driving variables of the underlying biogeochemical models into simulations. Consequently, GEMS can simulate not only the spatial and temporal trends of carbon dynamics such as $CO_2$ exchange between the terrestrial biosphere and the atmosphere but also provide uncertainty estimates of the predicted variables in time and space. A prototype of GEMS was successfully used for scaling nitrous oxide emissions from sites to the entire Atlantic Zone in Costa Rica (Reiners et al., 2002).

GEMS consists of three major components: one or multiple encapsulated ecosystem biogeochemical models, a data assimilation system (DAS), and an input/output processor (IOP). The CENTURY model was selected as the underlying ecosystem biogeochemical model in GEMS for this study because it has solid modules for simulating carbon dynamics at the ecosystem level and it has been applied to various ecosystems, including crops, pastures, forests, and savannas worldwide (Parton et al., 1987, 1994; Schimel et al., 1991, 1994; Pan et al., 1998; Liu et al., 1999; Reiners et al., 2002). This model simulates C, N, P, and S cycles in various ecosystems and has the capability of modeling the impacts of management practices, including land cover change, fertilization, cultivation, and natural disturbances, such as fire and hurricane (Parton et al., 1994; Ojima et al., 1994; Liu et al., 1999, 2004).

Because most information in spatial databases is aggregated to the map unit level, the direct injection of such information into modeling processes is often problematic and may result in potential biases (Kimball et al., 1999; Reiners et al., 2002). Consequently, data assimilation mechanisms are usually needed to incorporate field-scale spatial heterogeneities of state and driving variables into simulations. A DAS usually consists of two major interdependent parts: (1) data search and retrieval algorithms, and (2) data processing mechanisms. The first part searches and retrieves relevant information from various databases according to the keys provided by a joint frequency distribution (JFD) table (Reiners et al., 2002; Liu et al., 2004). Data processing mechanisms downscale the aggregated information at the map unit level to the field scale using a Monte Carlo approach.

When data are assimilated, they are incorporated into the modeling processes by means of the input/output processor, which updates the default input files with assimilated data. Values of selected output variables are also written by the IOP to a set of output files after each model execution.

#### *2.3.2. Geographic information system databases*

In addition to a series of land cover maps, spatially explicit geographic information system (GIS) databases of climate and soils were used to support biogeochemical modeling. Grids were generated at a resolution of 10-km-length scale to characterize the spatial and temporal patterns of monthly precipitation from 1961 to 1996. Long-term averages of monthly maximum and minimum air temperatures, also at a 10-km-length scale resolution, were used in modeling. Soil data were taken from inventory work done by Stancioff et al. (1986), including soil texture (i.e., fractions of sand, silt, and clay) and drainage class. Soil bulk density was set to $1.5\,\mathrm{Mg\,m^{-3}}$ according to Manlay et al. (2002b).

#### *2.3.3. Joint frequency distribution of major variables*

The JFD grid was generated from time-series land cover maps (i.e., the potential native vegetation and actual land cover from 1973, 1978, 1984, to 1990), soil, climate, and nature reserves at a common cell size of $80\,\mathrm{m} \times 80\,\mathrm{m}$. A total of 4423 unique combinations of these variables were generated with a frequency ranging from 1 to 10,518 grid cells. A model simulation was performed for each of the unique combinations. About 55% of the unique combinations had frequencies under 50 grid cells (i.e., 3.2 ha), suggesting that biogeochemical modeling was performed at a high spatial resolution and the spatial heterogeneity of these variables was high in the region.

#### *2.3.4. Land management practices*

Fallow is an important management practice that affects carbon dynamics and site fertility. Fallow practices are different in intensive, extensive, and old fields (Table 1). For example, the time-in-fallow is shortest for intensively cultivated agricultural land, followed by extensively cultivated land. The time-in-crop was set to zero in old

Table 1
Parameters used to define the characteristics of fallow practices in Velingara

| Land cover | Fallow probability | Time in crop (years) | | Time in fallow (years) | |
|---|---|---|---|---|---|
| | | Minimum | Maximum | Minimum | Maximum |
| *Business as usual* | | | | | |
| Intensive agriculture | 0.14 | 4 | 8 | 1 | 3 |
| Extensive agriculture | 0.50 | 3 | 6 | 3 | 6 |
| Bushland, old fields | 1.00 | 0 | 0 | 6 | 15 |
| *Agriculture intensification scenario* | | | | | |
| Intensive agriculture | 0.08 | 4 | 8 | 0 | 1 |
| Extensive agriculture | 0.25 | 3 | 6 | 1 | 2 |
| Bushland, old fields | 0.59 | 3 | 6 | 3 | 10 |

fields because time intervals between consecutive land cover images were shorter than the average age (10–20 years) of old fields. If a land parcel was classified as an old field, cropping was not likely to have occurred during the previous time interval. GEMS used these parameter values to stochastically generate fallow-cropping sequences on agricultural land parcels. At the end of fallow, wood is harvested for fuel, followed by burning. The cleared land parcel was then ploughed before the start of the rainy season.

Two levels of manure addition were distinguished for the intensive and extensive agricultural land. At the intensively managed fields, $3\,\mathrm{Mg\,C\,ha^{-1}\,year^{-1}}$ was added with a C/N ratio of 34. On the basis of our observations, it was assumed that half of the amount at the intensive sites was added to the extensive agricultural lands.

Bush fire has been used extensively for site management in all woodlands in Velingara. Fire frequency was set to once every other year, on the basis of expert knowledge. Based on field measurements, the fraction of live shoots removed by a bush fire was estimated to be 4%, 3%, 5%, and 8% for semi evergreen moist woodland, dry-deciduous woodland, savanna woodland, and bushland and shrubland, respectively. It is assumed that 90% of the standing dead plant material and surface litter is removed during a bush fire.

Biogeochemical modeling using the CENTURY model requires a detailed specification of cropping practices changes on agricultural land, including crop species and management practices. Remote sensing data provides only several general classes for agricultural land. In GEMS, a Monte Carlo technique downscales these aggregated classes to crop species on the basis of crop composition near the years when the remote sensing data were acquired (i.e., 1973, 1978, 1984, 1990, and 1999) (Table 2). Crop composition was derived from the agricultural census in Velingara.

Although the downscaled crop species in 1973, 1978, 1984, 1990, and 1999 provided a set of controlling points for defining agricultural activities, they were not sufficient because annual changes of cropping practices are required for biogeochemical modeling. In GEMS, crop rotation probabilities are used to determine the

Table 2
Temporal change of crop composition percentage on the basis of census data from the Department of Velingara

| Year | Crop | | | | | |
|---|---|---|---|---|---|---|
| | Millet | Sorghum | Cotton | Groundnuts | Maize | Rice |
| 1973 | 18.3 | 2.7 | 28.9 | 35.1 | 9.2 | 5.8 |
| 1978 | 26.2 | 8.8 | 16.1 | 25.4 | 12.0 | 11.4 |
| 1984 | 11.3 | 17.4 | 32.0 | 15.6 | 16.3 | 7.3 |
| 1990 | 9.5 | 21.6 | 14.7 | 15.9 | 27.2 | 11.1 |
| 1999 | 7.1 | 26.7 | 12.1 | 29.0 | 18.2 | 6.9 |

Table 3
Crop rotation probabilities in Velingara

| | Cotton | Fallow | Groundnut | Maize | Millet | Rice | Sorghum |
|---|---|---|---|---|---|---|---|
| Cotton | **0.31** | 0.08 | 0.33 | 0 | 0.28 | 0 | 0 |
| Fallow | 0.16 | **0.5** | 0.06 | 0 | 0.28 | 0 | 0 |
| Groundnut | 0.34 | 0.06 | **0.38** | 0 | 0.22 | 0 | 0 |
| Maize | 0 | 0 | 0 | **0.52** | 0 | 0 | 0.48 |
| Millet | 0.26 | 0.1 | 0.34 | 0 | **0.3** | 0 | 0 |
| Rice | 0 | 0 | 0 | 0 | 0 | **1** | 0 |
| Sorghum | 0 | 0 | 0 | 0.45 | 0 | 0 | **0.55** |

crops in the gaps between the predetermined crops resulting from downscaling. Crop rotation probabilities in Velingara (Table 3) were derived from 10 years of investigations and observations (Kairé, 1993, 1995, 1999).

Four major types of wood harvesting activities can be distinguished in Velingara. The first is commercial charcoal production, which appeared in the 1990s. Charcoal production results in the reduction of high-quality wood in forests. The second type of wood harvesting is for the production of commercial fuelwood, which usually harvests the wood not meeting the requirement of charcoal wood but still providing high combustion efficiency. The third type is to meet the need of domestic fuelwood consumption, which primarily consists of aboveground woody debris. The fourth type is to satisfy the requirement of domestic forest byproducts, such as house construction and furniture. Commercial harvesting activities exist only in savanna woodland, dense savanna woodland, and dry deciduous forests. Harvesting for domestic fuelwood and forest byproducts exists in all woodlands, forests, shrublands, bushlands, and fallow fields.

Rice is the only crop that receives irrigation in Velingara. Automatic irrigation was scheduled in the model to maintain 95% of the water requirements of rice. Rice and cotton receive fertilization in Velingara. The nitrogen fertilization level was about 30 kg N ha$^{-1}$ year$^{-1}$ for both crops. Grazing was specified with a frequency of every other month for all lands with trees. Grazing resulted in the removal of 10% and 5% of the live and dead understory biomass.

#### 2.3.5. Modeling design

*2.3.5.1. Carbon status around 1900: spinning-up simulations.* It is assumed in this study that carbon stock and fluxes in 1900 were near the equilibrium conditions under potential vegetation in Velingara. Although human existence in Velingara could be traced back before 1900, it is believed that the spatial extent of human disturbances on the landscape in Velingara was limited before 1900. Tropical dry forest and tropical moist forest were considered to be the potential land cover types in the area based on climate and local drainage conditions. Tropical moist forests were located along rivers, fossil river valleys, and the Anambe Basin.

Estimates of spatial patterns of carbon stock and fluxes in Velingara in 1900 were obtained by setting up GEMS to run for 1500 years under potential vegetation, climate information from 1961 to 1996 (repetitively used), and contemporary soil and drainage conditions. These estimates were used as the starting points for assessing the impacts of human land use activities on the amount of carbon change in the 20th century.

*2.3.5.2. Impacts of human disturbances on carbon dynamics from 1900 to 2000.* Starting from the estimated carbon status in 1900, GEMS simulated the impacts of human activities on carbon dynamics by incorporating land cover and land use change information. Land cover changes since 1973 have been captured by land cover maps generated in this study, but the exact historical trajectory of land cover change from 1900 to 1973 is poorly known and difficult to estimate. It is assumed that land cover change rate was constant from 1900 to 1973, meaning that if a change had occurred, the year of change was randomly selected between 1900 and 1973. The year of change, if any, during other time periods (i.e., from 1973 to 1978, from 1978 to 1984, etc.) was determined similarly.

*2.3.5.3. Climate change and carbon management from 2000 to 2100.* Climate change scenarios from 2000 to 2100 were based on the simulated results of seven global climate models (GCM) (Hulme et al., 2001). Three scenarios were considered in this study:

1. *No Climate Change Scenario* (*NCCS*): Climate conditions were based on observed precipitation and the maximum and minimum air temperatures from 1961 to 1996. These records were repetitively used during simulations.
2. *Low Climate Change Scenario* (*LCCS*): Changes in monthly precipitation and temperature based on their averages from 1961 to 1990 were calculated using the following equations derived from Hulme et al. (2001) for the study area:

$$\text{Precipitation}: \quad \text{change (\%)} = -0.2125 * \text{year} + 427.29, \ r^2 = 0.99. \tag{1}$$

$$\text{Temperature}: \quad \text{change (\%)} = 0.0142 * \text{year} - 27.71, \ r^2 = 0.99. \tag{2}$$

3. *High Climate Change Scenario* (*HCCS*): Similar to LCCS, changes in monthly precipitation and temperature were calculated using the following equations

derived from Hulme et al. (2001):

$$\text{Precipitation}: \quad \text{change (\%)} = -0.525*\text{year} + 1043.9,\ r^2 = 0.98. \tag{3}$$

$$\text{Temperature}: \quad \text{change (\%)} = 0.0638*\text{year} - 126.8,\ r^2 = 0.99. \tag{4}$$

Eqs. (1) and (3) were derived from the GCM predictions for precipitation in June, July, and August. Percentages of change were different in December, January, and February according to the GCM results. Because precipitation in Velingara is concentrated mainly from June to October and it rarely falls during the dry season (i.e., from December to February) (Fig. 1), we simply applied Eqs. (1) and (3) to calculate the precipitation change for all the months. Eqs. (2) and (4) were used to calculate monthly maximum and minimum temperatures from 2000 to 2100.

Although wood harvesting for commercial charcoal and fuelwood production can generate revenues for the Velingara economy, it will also have significant impacts on carbon dynamics in the region. In this study, we investigate the impacts of two wood-harvesting scenarios on carbon dynamics in the region for each of the three possible future climate scenarios. The first represents the business-as-usual scenario in which the current harvesting rates are maintained during the 21st century. In the second scenario, commercial wood harvesting activities are halted to increase carbon stock in the region and only domestic wood harvesting for biofuel and forest byproducts was allowed.

To investigate the impact of reducing fallow on C dynamics, two fallow scenarios were specified from 2000 to 2100 (Table 1). The first is the 'business-as-usual,' which is based on the conditions in the late 20th century. The second is the agricultural intensification scenario, which reduced fallow probability from 0.14–0.08, 0.5–0.25, to 1.0–0.59 on intensive, extensive, and old fields, respectively.

## 3. Results

### 3.1. Land cover change

Woodlands, including all the land except agricultural land, water bodies, and towns, are still the dominant land cover in the Department (Table 4). The woodland fraction decreased from 85% in 1973 to 63% in 1999. Meanwhile, the agricultural land fraction increased from 15% in 1973 to 34% in 1999. The area of dense savanna woodland area was reduced steadily, primarily by forest clearing and degradation. The results of the analysis of land use and land cover change are presented in Wood et al. (2004).

### 3.2. Model validation

The simulated spatial patterns of net primary productivity (NPP), live biomass carbon, SOC, and total ecosystem carbon from 1900 to 1996 are shown

Table 4
Temporal changes in the percentage of major land cover classes from 1973 to 1999 (Wood et al., 2004)

| Land cover class | Year | | | | |
|---|---|---|---|---|---|
| | 1973 | 1978 | 1984 | 1990 | 1999 |
| Dense savanna woodland | 30 | 29 | 26 | 25 | 21 |
| Dry deciduous woodland | 23 | 21 | 18 | 17 | 16 |
| Dense savanna woodland with bowe | 15 | 14 | 14 | 14 | 14 |
| Extensive Ag land with some fallow (1–3 years) | 9 | 11 | 8 | 9 | 13 |
| Bushland, old fields | 0 | 0 | 5 | 3 | 13 |
| Intensive Ag land with few fallow (0–1 year) | 6 | 8 | 14 | 17 | 8 |
| Savanna woodland | 8 | 8 | 6 | 6 | 5 |
| Moist semievergreen woodland, gallery forest | 4 | 4 | 3 | 3 | 3 |
| Riparian forest | 3 | 3 | 3 | 3 | 2 |
| Shrub savanna | 2 | 2 | 2 | 2 | 2 |

in Fig. 2. Apparently, tropical moist forests, distributed along the riparian zones and lowlands of the drainage basin (i.e., the midwest area), had higher carbon stocks in both biomass and soils under the equilibrium conditions. The simulated average live biomass C for tropical dry forests under equilibrium conditions was 88 MgC ha$^{-1}$, a stock that falls within the range of field measurements in this region (Table 5). It is also in general agreement with observations collected from dry tropical forests around the world (Brown and Lugo, 1982; Tiessen et al., 1998). The mean SOC in the top 20-cm layer was simulated to be 29 MgC ha$^{-1}$, which was in general agreement with field measurements (Table 5).

Few biomass measurements have been made for the tropical moist forest type in the region. The simulated live biomass and SOC content in the top 20-cm were 135 and 35 MgC ha$^{-1}$, respectively, agreed with observations in the tropical moist forest zone (Brown and Lugo, 1982; Hughes et al., 2002) and the high values observed in the region (Table 5).

Model-simulated grain yields agreed well with field survey data from the 1970s to 1990s (Fig. 3). Grain yield per hectare decreased from the 1970s to the 1990s, probably caused by the decline of annual precipitation during this period (Fig. 1). Simulated cropping areas corresponded closely with agricultural statistics (Fig. 3) except in 1999. The discrepancy between the simulated and surveyed cropland area in 1999 was explained by the significant increase in fallow area observed by remotely sensed imagery (see Table 4) or surveys (Fig. 3) that year. The model failed to catch the sudden increase in fallow area. We are not certain whether the sudden increase really happened or whether it was just an artifact of image interpretation.

Fig. 4 shows that simulated accumulation rates of aboveground and belowground biomass in fallow fields with different ages in the region agreed well with field measurements (Manlay et al., 2002a, b), when the biomass of stumps was not included. The CENTURY model does not simulate stump biomass explicitly.

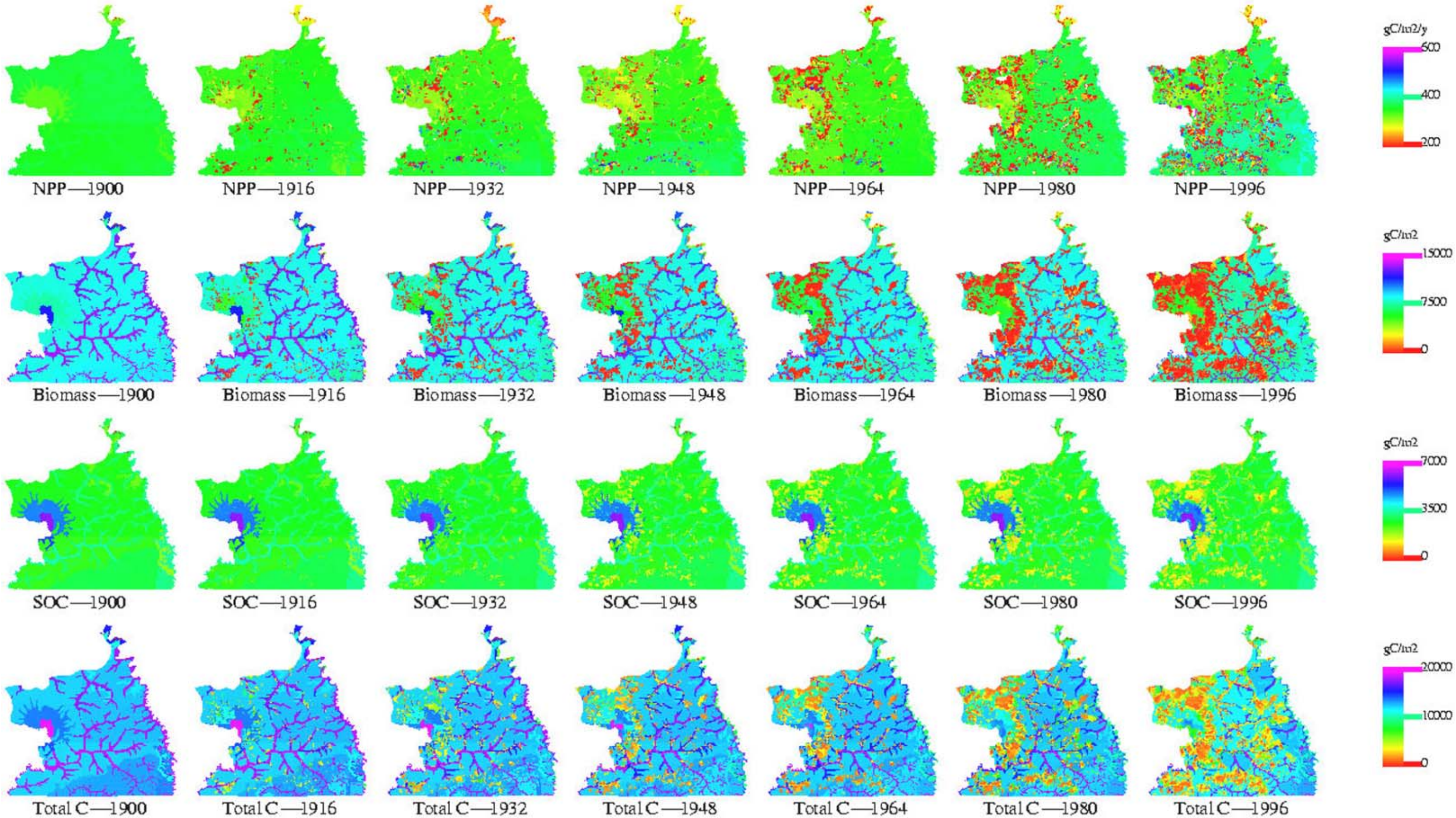


Fig. 2. Model-simulated changes of spatial patterns of net primary productivity (NPP), C stock in live biomass, soil organic carbon (SOC) in the top 20-cm layer, and total C stock in the Department of Velingara from 1900 to 1996.

Table 5
Field measurements of carbon stocks ($MgC\,ha^{-1}$) in vegetation and soils in Velingara. SOC contents in the top 0–20 cm layer were estimated from those in the 0–40 cm layer according to Jobbagy and Jackson (2000)

| Cover | Biomass | | SOC (0–40 cm) | | SOC (0–20 cm) | | $D^a$ |
|---|---|---|---|---|---|---|---|
| | Mean | Range | Mean | Range | Mean | Range | mean |
| Cropland | 1.9 | 0.9–4.0 | 29.9 | 15.0–56.0 | 19.2 | 9.6–35.9 | 1.57 |
| Fallow | 29.9 | 6.2–49.5 | 22.2 | 20.2–25.5 | 14.2 | 12.9–16.3 | 1.58 |
| Forest | 53.3 | 19.1–134.0 | 41.3 | 25.8–57.4 | 26.5 | 16.5–36.7 | 1.52 |
| Parkland | 20.0 | 19.4–20.5 | 18.8 | 17.0–19.8 | 12.0 | 10.9–12.7 | 1.42 |
| Savanna | 26.1 | 14.7–43.1 | 37.7 | 29.7–50.1 | 24.2 | 19.0–32.1 | 1.57 |

[a] Bulk density ($g\,cm^{-3}$).

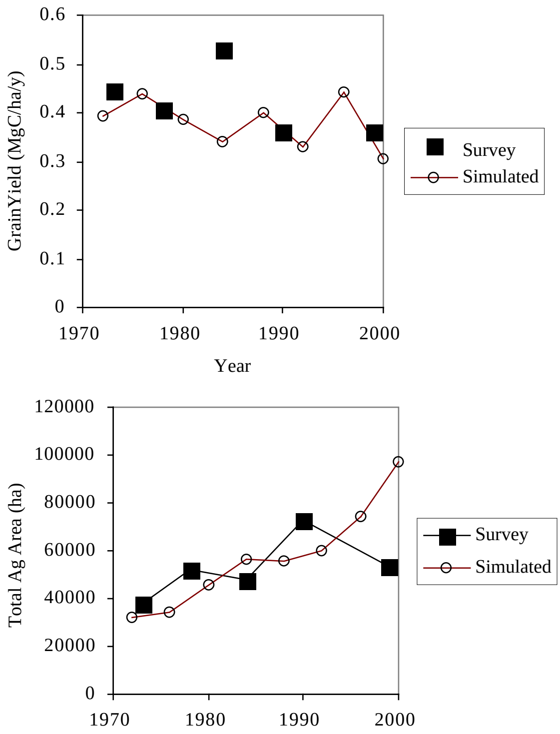


Fig. 3. Comparison between simulated and surveyed (1) crop yield and (2) total cropping area in Velingara. Simulated crop yield is the area-weighted average of all the six major crops in the region.

Stumps are not removed during cultivation in this region. The stumps remain alive and provide for the potential regeneration of trees after the farms are abandoned. Even if they account for 8% of the total stock carbon of the soil–plant system (Manlay et al., 2002a), stumps can be regarded as a pool not removed and not included in the simulation.

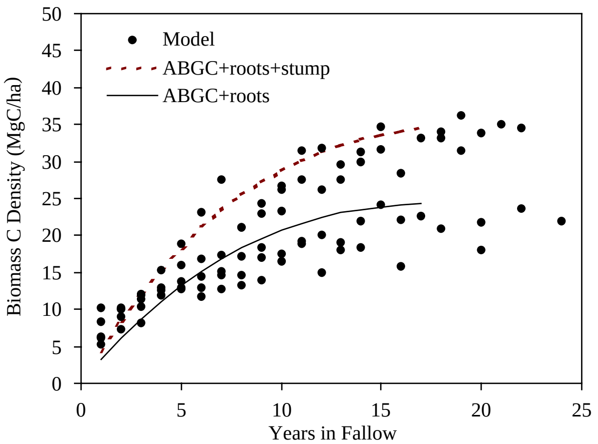


Fig. 4. Comparison of model-simulated relationship between biomass carbon density and fallow age with those derived from field measurements. Field-based relationships (i.e. the lines) were mainly derived from Manlay et al. (2002b). ABGC: aboveground biomass carbon (excluding the stumps).

### *3.3. Carbon dynamics in the 20th century*

Fig. 2 shows the spatial patterns of changes of NPP, live biomass C, SOC, and total system C every 16 years from 1900 to 1996 in Velingara. All significant changes during this period resulted from deforestation (mainly for agriculture) and forest degradation due to selective cutting. Human disturbances started in the midwest part of the region, and gradually expanded to the east. The rate of change has accelerated since the 1970s.

The average NPP fluctuated from 3 to 4 $\mathrm{MgC\,ha^{-1}\,year^{-1}}$ from 1900 to 2000 (Fig. 5). The annual fluctuation was mainly caused by precipitation variability. NPP in this region was largely controlled by the annual amount of precipitation, which falls within 4–5 months in the rainy season. Live biomass decreased gradually from 97 $\mathrm{MgC\,ha^{-1}}$ in 1900 to 74 $\mathrm{MgC\,ha^{-1}}$ in 1980. Biomass decreased more rapidly from 1980 to 2000 due to the accelerated conversion of forests to other land uses. Overall, live biomass was reduced by 46% during the 20th century. SOC decreased gradually from 30 $\mathrm{MgC\,ha^{-1}}$ in 1900 to 28 $\mathrm{MgC\,ha^{-1}}$ in 2000, representing a change of 8.5%. The simulated SOC in 2000 was close to the measured SOC stocks in forests and savannas (Table 5). Woody debris, including dead branches, dead stems, and dead large roots, changed from 11 $\mathrm{MgC\,ha^{-1}}$ in 1900 to 8 $\mathrm{MgC\,ha^{-1}}$ in 2000. The change of the temporal pattern of woody debris was greatly affected by forest harvesting activities, with significant short-time increases during periods of high input rates of residues from tree harvesting. The decline of woody debris in this region was caused by both the reduction of total forested area and the accelerated collection of woody debris as domestic fuelwood. Forest or woodland clearing for agriculture was the main wood harvesting activity before the 1990s. Since the 1970s, increased rates of forest clearing, and the introduction of selective harvesting for commercial charcoal

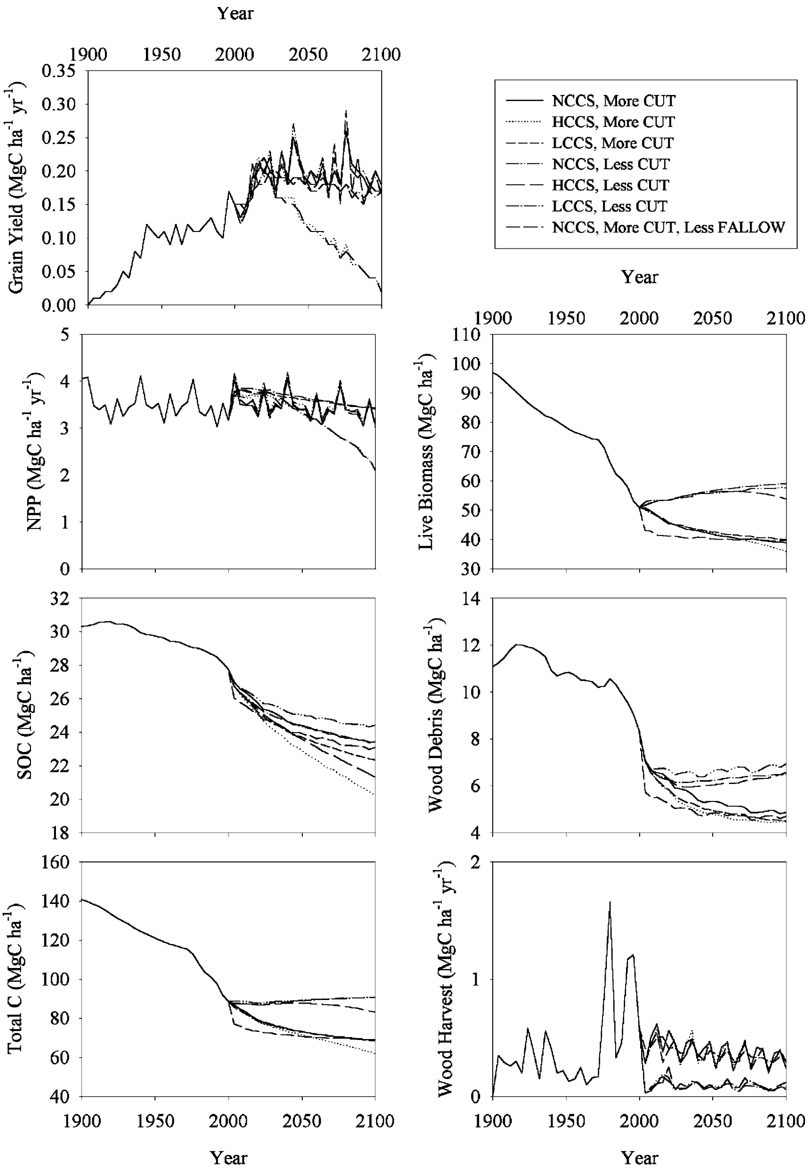


Fig. 5. Carbon dynamics from 1900 to 2100 in Velingara under various management and climate change scenarios. NCCS: No Climate Change Scenario; LCCS: Low Climate Change Scenario; HCCS: High Climate Change Scenario. Grain yield is calculated on the basis of total land area of Velingara.

and fuelwood production in the 1990s, contributed to the increase of the amount of wood being harvested during the last quarter of the century. The total C stock (i.e., live and dead above-ground and below-ground biomass C, and SOC in the top 20-cm soil layer) stock was reduced from 141 $MgC\,ha^{-1}$ in 1900 to 89 $MgC\,ha^{-1}$ in 2000, a reduction of 37%. Live biomass C accounted for 88% of the change, and SOC and litter accounted for the remaining 12%.

### 3.4. Carbon dynamics in the 21st century

Grain production was predicted to increase by about 25% on the basis of the values in the 1990s if the climate did not change (NCCS) or the change was small (i.e., under LCCS) (Table 6) (Fig. 5). Meanwhile, predicted grain production was relatively stable during the 21st century. However, the model predicted a dramatic linear decrease in grain production over time under the large climate change scenario (HCCS). The change was caused by a 58% decrease in precipitation during this period. The annual precipitation around 2100 would be reduced to 350 mm according to the predictions of some GCMs (Hulme et al., 2001).

The average NPP is expected to decline 10% under NCCS and LCCS (Fig. 5). This decline might be caused by the continuous harvest of nutrients from the ecosystems through grain and wood harvesting. The rate of nutrient harvest was higher than the input through atmospheric deposition and application of chemical fertilization. NPP responded nonlinearly to the linear decrease of precipitation under HCCS. It remained unchanged for the first quarter of the century, and by 2100 it had decreased gradually to about 60% of the 2000 value (Fig. 5).

The most significant factor affecting the amount of C stock in above- and below-ground live biomass was selective wood harvesting for commercial fuelwood production (Fig. 5). Eliminating fuelwood production (i.e., cutting less to satisfy only domestic requirements for wood products) would increase C stock in live biomass under NCCS and LCCS, while C stock would increase in the first half of the century and then decrease under HCCS. Carbon stock would decrease gradually if the wood harvest schemes in the 1990s were continued. The decline rates under NCCS and LCCS were comparable and decreased gradually over time. In contrast, the decline rate under HCCS was close to that under NCCS and LCCS during the first 50 years and increased thereafter. Reduced fallow had little impact on live biomass C in the region, which was expected because fallow only affects the live biomass C in agricultural land and bushland, both of which have relatively low biomass and area coverage.

SOC is predicted to decline continuously over time under all management and climate change scenarios (Fig. 5). At the end of the century, SOC would be reduced by about 3.3–6.9 $\mathrm{MgC\,ha^{-1}}$, representing decreases of 12–25% on the basis of the values in 2000. More selective cutting (i.e., sustained commercial fuelwood production) caused only 0.9, 1.0, and 1.0 $\mathrm{MgC\,ha^{-1}}$ additional SOC loss compared with less cutting under NCCS, LCCS, and HCCS, respectively. Reduced fallow had little impact on the change of SOC stock at the regional scale owing to the limited extent of agricultural land in the region. The reduction of SOC stock was accelerated by climate change with 1.0 and 2.6 $\mathrm{MgC\,ha^{-1}}$ additional loss under LCCS and HCCS, respectively, compared with that under NCCS.

Woody debris varied from 4.5–4.9 $\mathrm{MgC\,ha^{-1}}$ in 2100 if the commercial selective cutting was continued, indicating a loss of 3.3–3.8 $\mathrm{MgC\,ha^{-1}}$. Abandonment of the

Table 6
Simulated dynamics of carbon stocks and fluxes in Velingara from 2000 to 2100 under various management and climate change scenarios

| | | NCCS, more cut | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | NCCS, more cut | NCCS, less cut | Less fallow | LCCS, more cut | LCCS, less cut | HCCS, more cut | HCCS, less cut |
| Grain yield ($MgC\,ha^{-1}\,year^{-1}$) | 2001–2025 | 0.18 | 0.19 | 0.18 | 0.18 | 0.18 | 0.17 | 0.17 |
| | 2026–2050 | 0.21 | 0.21 | 0.22 | 0.19 | 0.19 | 0.15 | 0.15 |
| | 2051–2075 | 0.19 | 0.20 | 0.19 | 0.18 | 0.18 | 0.10 | 0.10 |
| | 2076–2100 | 0.20 | 0.20 | 0.20 | 0.17 | 0.17 | 0.05 | 0.05 |
| NPP ($MgC\,ha^{-1}\,year^{-1}$) | 2001–2025 | 3.59 | 3.74 | 3.64 | 3.76 | 3.82 | 3.68 | 3.77 |
| | 2026–2050 | 3.52 | 3.62 | 3.57 | 3.67 | 3.72 | 3.52 | 3.57 |
| | 2051–2075 | 3.35 | 3.42 | 3.41 | 3.57 | 3.58 | 3.10 | 3.10 |
| | 2076–2100 | 3.39 | 3.43 | 3.45 | 3.46 | 3.46 | 2.52 | 2.52 |
| Live biomass ($MgC\,ha^{-1}$) | 2001–2025 | 48 | 53 | 48 | 48 | 53 | 47 | 53 |
| | 2026–2050 | 43 | 55 | 44 | 44 | 56 | 43 | 55 |
| | 2051–2075 | 41 | 56 | 43 | 42 | 57 | 41 | 56 |
| | 2076–2100 | 39 | 57 | 42 | 40 | 59 | 38 | 55 |
| SOC ($MgC\,ha^{-1}$) | 2001–2025 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |
| | 2026–2050 | 25 | 25 | 25 | 24 | 25 | 24 | 24 |
| | 2051–2075 | 24 | 25 | 24 | 23 | 24 | 22 | 23 |
| | 2076–2100 | 24 | 24 | 24 | 23 | 24 | 21 | 22 |
| Woody debris ($MgC\,ha^{-1}$) | 2001–2025 | 6 | 7 | 6 | 6 | 6 | 6 | 6 |
| | 2026–2050 | 6 | 6 | 5 | 5 | 6 | 5 | 6 |
| | 2051–2075 | 5 | 7 | 5 | 5 | 6 | 5 | 6 |
| | 2076–2100 | 6 | 7 | 5 | 5 | 6 | 4 | 6 |
| Harvested wood ($MgC\,ha^{-1}\,year^{-1}$) | 2001–2025 | 0.47 | 0.10 | 0.48 | 0.45 | 0.10 | 0.46 | 0.11 |
| | 2026–2050 | 0.41 | 0.09 | 0.39 | 0.38 | 0.10 | 0.39 | 0.09 |
| | 2051–2075 | 0.36 | 0.09 | 0.35 | 0.35 | 0.08 | 0.37 | 0.10 |
| | 2076–2100 | 0.32 | 0.07 | 0.31 | 0.32 | 0.08 | 0.32 | 0.09 |
| Total C ($MgC\,ha^{-1}$) | 2001–2025 | 82 | 88 | 82 | 81 | 87 | 81 | 87 |
| | 2026–2050 | 75 | 89 | 76 | 75 | 88 | 74 | 87 |
| | 2051–2075 | 72 | 90 | 74 | 72 | 90 | 69 | 87 |
| | 2076–2100 | 70 | 90 | 72 | 69 | 90 | 64 | 85 |

NCCS: No Climate Change Scenario; LCCS: Low Climate Change Scenario; HCCS: High Climate Change Scenario.

commercial wood harvest would result in 6.4–6.8 $MgC\,ha^{-1}$ woody debris in 2100. Climate change had little impact on C stock in woody debris.

Carbon loss due to wood harvesting decreased if the current commercial wood harvesting activities were continued, mainly a consequence of the reduction of live biomass stock. Without commercial wood harvest, carbon in harvested wood was relatively stable. Climate change and agricultural intensification (i.e., reduction of fallow) had little impact on harvested wood C.

Total C stocks in vegetation and soils remained stable under NCCS and LCCS if the commercial wood harvesting were halted, while large climate change resulted in the loss of $5\,\mathrm{MgC\,ha^{-1}}$ (Table 6). Continuous commercial wood harvesting led to $20\,\mathrm{MgC\,ha^{-1}}$ of additional reduction in total C stock under all climate change scenarios. Reduced fallow sequestered $2\,\mathrm{MgC\,ha^{-1}}$.

## 4. Discussion

Management of forests, croplands, and pastures affects the sources and sinks of $CO_2$ and other greenhouse gases, such as methane and nitrous oxide (Keller and Reiners, 1994; Weitz et al., 1999; Reiners et al., 2002). The Kyoto Protocol calls for the promotion of sustainable development in the course of reducing greenhouse gas emissions, including an increase of carbon sequestration in or a reduction of carbon release from terrestrial ecosystems. It explicitly identifies the achievement of sustainable development as a central purpose and a requirement for project activities through the CDM. Consequently, initiating C sequestration projects will most likely face a series of decisions and tradeoffs on a broad range of socioeconomic and environmental issues, such as food security, biodiversity, employment, and equity.

Avoiding deforestation can reduce the release of C into the atmosphere and also provide habitat for animal and plant species, pasture for livestock, wood for shelter, timber, and fuelwood, and land for agriculture, and it can have a favorable effect on weather and climatic patterns. A large proportion of the forest in the Department of Velingara has been protected. However, pressure has been increasing on these protected forests because of population growth, agricultural expansion, and fuelwood and charcoal production. Disturbances such as fallow and forest degradation owing to selective logging are present in certain parts of the protected forest areas. How to protect these areas under ever-increasing human pressure is one of the serious challenges in the protection of dry tropical forest ecosystems in Africa in general. Although avoiding deforestation cannot be credited to C sequestration during the first commitment period, future inclusion of the avoided C emissions into the CDM may be possible. Additional income from selling C sequestration credits will probably increase the efficiency of forest protection in the region.

After the conversion of forest to agricultural land, SOC decreases by 20–40% in general (Donigian et al., 1994; Paul et al., 1997; Buyanovsky and Wagner, 1998; Tiessen et al., 1998; Fearnside and Barbosa, 1998; Harden et al., 1999). Forest clearing for shifting cultivation releases less C than permanent forest clearing because the fallow period allows some forest regrowth. The carbon accumulation rate on abandoned land depends on previous land use history, the length of fallow, the type of soil, and climate conditions of the site (Brown and Lugo, 1982; Paul et al., 1997; Hughes et al., 1999, 2002; Manlay et al., 2002a, b, c). Some SOC is also lost during shifting cultivation, but less than during continuous cultivation if the length of fallow is long. However, because shifting cultivation usually has lower productivity than permanent cultivation owing to less management intensity and lower nutrient input, more forest land would have to be cleared to provide the same amount of agricultural products assuming that agricultural productivity would not change significantly. Although it is very important in C sequestration accounting, no study has been done on the difference of fallow vs. continuous cultivation on C dynamics at the regional scale, given the constraint of providing the same products. Previous studies investigate the differences at the plot scale (Olsson and Ardö, 2002), which is not sufficient in carbon accounting without addressing the difference of total areas affected by the two cultivation practices.

Management practices (e.g., irrigation and fertilization) can enhance SOC stocks in croplands. Fertilization with N and P can be very effective in enhancing agricultural production and therefore might lead to an increase in SOC stock or at least minimize the decrease brought about by tillage, harvesting, and other agricultural management practices. In addition to the possibility of water and soil pollution, the application of fertilizers in croplands is one of the largest human-induced sources of greenhouse gas nitrous oxide emission at present (Kroeze et al., 1999; Reiners et al., 2002). The potential of applying fertilizers for carbon sequestration should be evaluated with the increased $N_2O$ emissions in mind.

Biomass energy can be used to replace fossil fuels, thereby reducing greenhouse gas emissions from fossil fuel burning. The avoided fossil fuel C emissions of a biomass energy system are equal to the fossil fuels replaced minus the fossil fuels used in the biomass energy system (IPCC, 2000). Selective logging for fuelwood and charcoal production has existed in the Department of Velingara since the 1990s. Almost all unprotected forests in this region have been selectively logged for biomass energy. Fuelwood (both fuelwood and charcoal) production has led to an immediate decrease of standing biomass or C stock in forests. However, because fuelwood production is selective and only certain trees of some species are harvested, affected forests have a constant minimum stock of C. Sprouts usually grow from the stumps of harvested trees, sequestering C for the next round of biomass fuelwood production. In this practice, forest land can therefore be used continuously for the production of fuelwood to replace fossil fuels.

The recovery rate of biomass or strength of the C sink after selective logging is determined by harvesting intensity, the level of disturbances during harvesting, and local climate, and soil and management conditions. In the short term, harvesting followed by natural regrowth has a limited effect in most cases (Johnson et al., 2002). No field observation was available regarding the impact of fuelwood production on SOC in the region. Modeling results indicated that fuelwood production had little impact on SOC dynamics, which is consistent with field observations worldwide (Johnson et al., 2002). However, it is expected that the productivity and SOC level of the forests would decrease owing to the continuous harvest of nutrients through selective logging (Table 6). The only nutrient input for the forests in this region is the wet and dry atmospheric deposition (about $5\,kg\,N\,ha^{-1}\,year^{-1}$), which is not enough to balance the export. It is necessary to fertilize the forests in order to maintain the productivity of the forest ecosystems in the region. However, forest fertilization is unrealistic at present and in the near future without direct support from industry.

## 5. Summary

No internationally agreed upon methods exist to quantify carbon emissions and sequestration over large areas. Such methods are urgently needed if land use-related C sequestration projects are to be developed, evaluated, monitored, and reported consistently and credibly across projects and regions. Accepted methods should be able to quantify the spatial dynamics of carbon sources and sinks to address many project-related questions, such as leakage, and permanence in general or out of the scope of projects (e.g., at the national scale). The spatially explicit modeling approach presented in this study, coupled with a stricter design of field plots for validating model-simulated results, provides a potentially credible, consistent, and practical system for accounting for C dynamics in space. The approach and model developed in this study is generic and can be easily adapted for the simulations of carbon dynamics in vegetation and soils under various climate change and management scenarios over large areas.

Future climate change poses a great threat to food security in the region. Annual precipitation in the study area is predicted to diminish about 58%, to 350 mm. Unless the decrease of precipitation is addressed by agricultural intensification, specifically the adoption of irrigation technology, agricultural land is expected to expand at the expense of forests and woodlands. This will definitely make the estimation of baseline and carbon sequestration potential more challenging.

Managing woodlands and forests as a sustainable fuelwood and charcoal production system can be a practical and important carbon sequestration project in the region. The impact of the agricultural sector on regional C dynamics is limited because of the limited extent of agricultural land. Consequently, few significant choices exist for setting up agricultural-based C carbon projects in the region. However, carbon dynamics in the agricultural sector may become more important if agricultural land is expanded owing to the changes in socioeconomic and environmental conditions, including population and climate.

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